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I. INTRODUCTION

Blanket design studies⁽¹⁾⁽²⁾⁽³⁾ made by BNL engineers have focused on two principal goals, minimum activity and modularity. Since service life cannot be predicted at this point in the development of tokamak reactors, modularity, and plans to remove and replace modules must be included in the design process. Low activity also intersects the removal problem in a most direct way. It also intersects the problem of ultimate storage. Kulcinski⁽⁴⁾ recently estimated a materials requirement of 0.3 to 0.4 Mt/Mw(t) and 10^6 MW(e) from fusion by mid 21 century. Making reasonable assumptions as to conversion efficiency and materials density, the production every 5 years of radioactive material (which would have to be sequestered for many decades) would form a mound approximately the size of the great pyramid of Cheops. Low activity blankets such as that described herein have the potential of reducing this mammoth waste disposal problem to more manageable proportions.

From the BNL design studies, two basic designs have evolved, one compound mostly of graphite with SAP tubes carrying helium as coolant and the other composed of cylindrical aluminum canisters filled with a ceramic bed of moderating, shielding, and breeding materials all suitably cooled. This

paper presents design details representing the current state of developments for this latter blanket type.

The aluminum canister module can take several forms, all of which have the following features in common:

- 1) A long (approximately 5 to 10 meters) cylindrical shell made of wrought aluminum alloy (5000 series), SAP, or FP (fiber product aluminum).

- 2) A small number of such shells typically 3 to 6, mounted on an aluminum backing plate to form a "unit" insofar as assembly and disassembly is concerned.

- 3) Cooling passages carrying water or helium to hold the shell temperature within prescribed limits.

- 4) The module interior to be filled with a ceramic bed of materials such as graphite, silicon carbide, boron carbide and a solid lithium compound if tritium breeding is desired, etc., suitably shaped to permit cooling by interstitial flow of hot helium.

- 5) All coolant passages to be "down and back" so that manifold connections are at one end only thereby facilitating replacement of modules.

- 6) Internal insulation to segregate the relatively cool metal shell from the substantially hotter ceramic interior parts.

II. PHYSICAL DESCRIPTION

The bulk of this paper deals with a blanket fitted to a circular plasma (see Fig. 1) reactor corresponding to the ANL-TEPR design⁽⁵⁾; however, work in progress has included designs for non circular plasmas and for commercial reactors as well.

Since at this point in the development of fusion reactor technology, it is impossible to speak with assurance of the useful life of components, we have elected to design the blanket in a modular fashion so that should replacement of any modules be required, it could be accomplished with reasonable effort.

We view the overall blanket region as a short cylinder with an octa decagon cross section. The cylinder has vertical inner and outer walls and horizontal wedge shaped top and bottom surfaces. The individual blanket modules completely cover these surfaces in the case of the EPR design and cover all but the divertor slot in the case of a commercial reactor.

Figure 2 shows schematically how the blanket and shield are assembled. The shield forms a fixed structure from which the blanket modules are supported and also provides the primary vacuum seal. Blanket canisters are mounted on heavy aluminum backing plates forming modules which are in turn supported from the fixed shield.

Figure 3 shows how the modules compare in the case of the EPR and a commercial reactor with a UWMAK size plasma. For the EPR, the module is 1m wide x 4.8m long x 0.7m thick. It holds 3 canisters, each 33 cm wide x 4.8m long x 50cm thick for a total weight of about 7 mtons. Modules for the UWMAK size plasma are basically similar and are somewhat larger with 6 canisters per module, each canister being 11m long.

Continuing with the EPR case, Figure 4, a representative 20° sector of the torus, shows the three vertical outer modules and the one vertical inner module. It also shows the taper associated with each 20° sector. To cover this tapered section with modules requires three module types, as seen in Figure 5 the central unit being similar to the vertical side wall modules, and left hand and right hand tapered modules. As seen in Fig. 5, the left hand tapered module is actually composed of foreshortened canisters to match the sector taper. As shown, these foreshortened canisters intrude into the taper space of the adjacent sector. This figure also indicates that one of the side modules (the right hand one of Fig. 5) might be eliminated entirely to provide beam holes, vacuum ports, etc. or alternately could consist of severely foreshortened canisters and graphite filler pieces.

The complete blanket consists of 72 vertical modules and 108 horizontal modules arranged so that any one of the 10 modules associated with each 20° sector can be removed through two relatively small access ports per sector. Figure 6 shows the lower access port. It should be noted that the size of this access port is somewhat larger than a single module, is located on the sector centerline and also contains all the header connections to the lower horizontal modules. A section view thru this same access port is shown in Figure 7, and a similar view thru the upper access port is shown in Figure 8. The access port is closed by a removable shield plug which may be water filled, the water being discharged when the plug is pulled.

Figures 9 and 10 show track arrangements in the fixed shield structure which together with the access ports just mentioned permit replacement of any module in the blanket. To remove the lower central module, valving in the coolant headers would be shut off, after which the quick disconnects in the lines outside the shield plug would be opened; then the vacuum seals around the shield plug would be cut. All this is done on the outside of the shield and can be accomplished by direct access. The removable shield plug is then removed and finally the bottom central module rolled out

on its roller pad supports. To remove either the left or right side tapered modules, the central module would be removed followed by movement of the side module, first to the center module position (i.e., sidetracking) then out thru the access port.

The upper horizontal modules and outside vertical modules are removed in a similar manner thru the upper access port, in each case the central module being removed before the side module can be removed.

Replacement of course follows the same procedure in reverse order.

Figure 12 shows some of the design concepts being considered for the canisters. One concept embodies three oval shaped cylindrical canisters bolted to the aluminum backing plate to form a unit. Presently we prefer this concept if stresses can be held to within reasonable limits. A modification of this concept embodies 6 circular cylindrical canisters. This concept increases the header and support problems but stress-wise would be better than the oval concept. Figure 11 shows schematically the shell cooling configuration. The inlet and outlet headers run the full length of the canister. From these headers, individual coolant passages carry the shell coolant circumferentially

around the canister wall. Detailed analysis leading to the dimensions shown on this figure are presented in section 3.3. Two cases are shown on Fig. 11 namely a water cooled shell (water in at 189°C , out at 204°C at 300 psia) and a helium cooled shell (helium in at 200°C , out at 380°C at 600 psia). The water cooled shell uses a wrought aluminum alloy (5000 series) while the helium cooled shell uses SAP.

A summary of the blanket process conditions for both the water cooled first wall and for the helium cooled first wall are shown in Table 2.1.

A two dimensional, plane strain finite element analysis has been used to determine stress in the blanket modules due to the 300 psi internal pressure. Canisters formed by two hemicylindrical heads connected by straight sections, with a thickness of 2.5 cm, exhibit unacceptable stress levels when they are located at the ends of the module so that lateral support from adjacent canisters cannot be assumed. Excessive bending causes stresses in the 25 ksi range. The shape shown in Figs. 24 and 25 is designed to reduce the bending by stiffening the sides of the canisters. As shown, the vertical portion of the 2.5 cm shell wall is reinforced by a tapering support 5.5 cm at its base made of fiber product (FP) aluminum material. This support is cantilevered from the module's base plate and

Table 2.1

Typical Thermal and Hydraulic Characteristics
of the Aluminum Blanket at 0.5 MW/M² Wall Loading for an EPR

Nominal Reactor Power	300 MW
Fraction of Power to Cold Circuit	0.45
Fraction of Power to Hot Circuit	0.55

Cold Circuit Conditions

	<u>Option</u>	
	<u>5000 Series</u>	
	<u>Al</u>	<u>SAP</u>
Coolant	Water	He
Inlet Temperature, °C	189	200
Outlet Temperature, °C	204	380
Operating Pressure, psia	300	600
Flow Rate, g/sec	4.30x10 ⁶	2.87x10 ⁵
Channel Velocity, cm/sec	420	3500
Heat Transfer Coefficient, w/cm ² -°C	4.59	0.35
Blanket Pressure Drop, psia	29	13.5
Pumping Power as Fraction of Total Power	0.003	0.022

Hot Circuit Conditions

Coolant	He
Inlet Temperature, °C	400
Outlet Temperature, °C	800
Operating pressure, psia	300
Flow Rate, g/sec	7.9x10 ⁴
Channel Velocity, cm/sec	2200
Heat Transfer Coefficient, w/cm ² -°C	0.08
Blanket Pressure Drop, psia	8
Pumping Power as Fraction of Total Power	0.01

Blanket Conditions

	<u>Option</u>	
	<u>5000 Series</u>	
	<u>Al</u>	<u>SAP</u>
Maximum First Wall Temperature, °C	215	400
Maximum Carbide Bed Temperature, °C	1450	1450

attached to the shell wall. Fiber produce is an extremely tough aluminum composite with an elastic modulus of 30×10^6 psi. The indicated support would only be used at the outside walls of the two extreme canisters in each module. As illustrated in the figures, a small boss at the shoulder of the canister is designed to butt up to a similar boss on the adjacent module thereby restricting lateral movement in the outside canister wall. By using a small raised surface, instead of the entire vertical wall, for lateral support between modules the machining tolerance problems are considerably lessened.

With the FP reinforcement and lateral support from adjacent modules the stress in the canisters are greatly reduced. The maximum stress is 3500 psi in the aluminum wall with average stresses through the wall around the 2,000 psi level. Figure 24 shows the stresses at various critical locations for this case. As can be seen all stress values are now at acceptable levels. Even if for some of the canisters the adjacent module does not provide lateral support the stress values in the FP reinforced design are significantly reduced from those in the unsupported design. This case is illustrated in Fig. 25. Now a maximum stress of 12,400 psi is reached at the canister shoulder where the FP support begins. Bending stresses at top center of the canister are also higher, reaching a value of 7800 psi. In

both cases average stresses through the wall are much lower, so that, while local yielding at the highly stressed edges may occur, the integrity of the wall will be preserved. In the finite element analysis of this shape the canister is assumed to be symmetrical about its vertical center line. In actuality the inside wall of any outside canister is supported by the wall of the adjacent internal canister in the same module so that the stresses calculated using the symmetry assumption are probably larger than would actually be experienced in the outside wall. (It should be noted that module canisters internally located have their vertical walls supported laterally along their entire height by adjacent canisters. Under these conditions stresses in the canister walls are below 2,300 psi everywhere. Therefore the relatively high stress values discussed above refer only to the outside canisters of each module.) The 12,400 psi stress value as well as the other stress values in Fig.25 can be further reduced by thickening the FP support and bringing it up higher on the outside shell wall. Better fairing of the support with the wall will also reduce stresses.

It must be pointed out that such effects as thermal cycling or prolonged radiation which will influence canister strength have not been taken into account in the above analysis.

III. TECHNICAL ANALYSIS OF EPR DESIGN

Design of anything as technically involved as a tokamak blanket is by its very nature an iterative process. Starting with basic premises, broad decisions are made which are then examined, carefully analyzed and evaluated and then a second round of decisions made or modification made to earlier decisions and the whole cycle of analysis repeated. Depending on the number of iterations made, one can refer to the design as a conceptual design or a feasibility study or in the ultimate an optimum design. Engineering studies of fusion blankets are at best conceptual designs or feasibility studies. True optimization is necessarily well off into the future although some measure of local optimization is possible in feasibility studies.

The basic criteria used for the EPR analysis were: 1) a plasma burn time of 30 sec on and 30 sec off; 2) a wall loading of 1 MW/m^2 during the on cycle, resulting in an average loading of 0.5 MW/m^2 for the entire cycle; 3) ANL-TEPR plasma dimensions (see Fig. 1) and 4) no breeding. Other basic criteria had to do with limiting materials temperatures. In the case of the wrought aluminum alloy (5000 series) the temperature was limited to about 200°C while in the case of SAP the temperature was set at 400°C . For the ceramic materials

inside the canister, no attempt was made to push them to their temperature limits but rather to base the hot helium temperatures on existing HTGR technology, it being fully recognized that at some future date an optimization might indicate higher temperatures.

These basic premises led to a canister design essentially 33 cm x 50 cm x 5 m with an aluminum wall about 2.5 cm thick. This aluminum canister constitutes the first wall. Immediately behind the insulated aluminum wall and extending for approximately 20 cm is a region of silicon carbide blocks in which most of the neutron moderation takes place. Behind the SiC blocks, there is 30 cm of B₄C in which the remainder of the neutron slowing down and absorption occurs. Thus the bulk of the fusion energy is absorbed by these high temperature ceramic materials from whence it is transferred to the helium stream at temperatures of the order of 700-800°.

3.1 Neutronics

Each blanket module was subdivided into a number of zones and within each zone, the components were homogenized for the one dimensional ANISN⁶ calculations. The geometry of the reactor is represented as an infinite cylinder (with its axis in the center of the plasma) with a vacuum boundary condition at the outer radius. A P₃ option was used for the order of angular scattering and an S₈ option for angular

quadrature. The 14.1 MeV source neutrons are taken to have a uniform spatial distribution in the plasma region. The coupled neutron and gamma-ray cross sections (for 100 neutron energy groups and 21 gamma-ray energy groups) together with the neutron and gamma-ray kerma factors are supplied by the data library DLC-37.⁷

The cylindrical geometry used in the calculations approximated the actual geometry of the reactor designs by equating the cross sectional areas of corresponding zones in the cylindrical and actual geometries. The wall loading was 1.0 megawatts (thermal)/m². The compositions, volume fractions and dimensions of each zone are given in Table 3.1 for the helium cooled shell.

The total neutron fluxes are shown in Fig. 13. On each curve there is indicated the boundary between the blanket module and its thick aluminum backing plate as well as the boundary between the aluminum backing plate and the shield. Fig. 14 shows the total heat deposition rates due to neutron and gamma heating as a function of distance from the first wall. The sudden rise in the heat deposition rate in the aluminum modules at about 20 cm is a consequence of the B₄C which starts at this point. The neutron energy escaping from the shield is about 10 eV/fusion neutron for the circular aluminum case.

Table 3.1

Blanket Dimensions and CompositionsAluminum Shell Blanket

<u>Region</u>	<u>Material</u>	<u>Circular</u>		<u>Non-Circular</u>	
		<u>Thickness (cm)</u>	<u>Volume Fraction</u>	<u>Thickness (cm)</u>	<u>Volume Fraction</u>
1	Plasma	210.0	1.0	169.26	1.0
2	Vacuum	59.0	1.0	16.93	1.0
3	Aluminum	2.46	1.0	2.46	1.0
4	Vacuum	0.12	1.0	0.12	1.0
5	Al ₂ O ₃	0.62	1.0	0.62	0.20
6	Vacuum	1.19	1.0	1.19	1.00
7	Al ₂ O ₃	0.25	1.0	0.25	1.00
8	{ SiC		0.74		0.74
	{ Aluminum	14.05	0.10	5.0	0.10
	{ Al ₂ O ₃		0.03		0.03
9	{ B ₄ C		0.70		0.70
	{ Aluminum	21.9	0.12	8.0	0.12
	{ Al ₂ O ₃		0.05		0.05
10	{ B ₄ C		0.55		0.55
	{ Aluminum	5.5	0.12	3.5	0.12
	{ Al ₂ O ₃		0.05		0.05
11	Al ₂ O ₃	0.5	1.00	0.5	1.00
12	Vacuum	0.1	1.00	0.1	1.0

Table 3.1 (cont.)

<u>Region</u>	<u>Material</u>	<u>Circular</u>		<u>Non-Circular</u>	
		<u>Thickness</u> <u>(cm)</u>	<u>Volume</u> <u>Fraction</u>	<u>Thickness</u> <u>(cm)</u>	<u>Volume</u> <u>Fraction</u>
13	Aluminum	20.0	1.00	15.0	1.0
14	{ Aluminum			15.0	0.90
	{ Water				0.10
15	{ B ₄ C	70.0	0.80	55.0	0.80
	{ Aluminum		0.20		0.20

ASSUMED DENSITIES (Gms/cc)

Aluminum	2.70
Al ₂ O ₃	4.00
B ₄ C	2.52
Water	0.80
SAP	2.75
SiC	2.73

3.2 Thermal Analysis

Since two coolant circuits are contemplated, it is imperative to determine the total heat flow in each circuit. We now examine the heat flows to the canister circuit.

Bremsstrahlung amounts to 3.5 Mev of the total 17.4 Mev deposited or 20%. This is all deposited within the first few millimeters of the first wall, essentially a surface effect.

Neutron and gamma ray heating of the first wall amounts to about 2.2 W/CC which for a 2.5 cm thick wall amounts to an additional 11%.

Neutron and gamma ray heating of the side walls can be approximated by

$$q = q_0 e^{-.083 x}$$

where q_0 is the heating rate at the first wall and x is the distance away from the first wall. For the basic canister dimensions selected, this amounts to an additional 8.1%.

Heat leakage from the hot interior region depends on the temperature levels in the canister wall and in the interior, the amount and quality of insulation used, and the contact area. Using 2.5 cm thick layer of graphite felt with a thermal conductivity of 0.0036 W/cm²/K results in an additional heat flow of 5.5% in the water cooled case and somewhat less in the helium cooled case.

Thus the total heat pick up in the canister wall cooling circuit amounts to 45% of that generated by the plasma. The remaining 55% is absorbed in the hotter interior. (It should be noted that if circular canisters are used the wall may be approximately 1 cm thick or slightly thicker thus reducing the heat pick up in the canister wall by neutron and gamma ray absorption and the resulting split between the wall circuit and the interior circuit becomes 35%-65%).

Having determined the heat pick up in the canister wall, the coolant flow can be established consistent with previously established aluminum temperature limits. Since in the present instance, the coolant passages occupy but a small portion of the shell wall, detailed thermal analysis seemed warranted. Optimization of the location of these coolant passages or of their dimensions has not been attempted. Based on an arbitrary (seemingly reasonable) choice of dimensions (see Figs. 26 and 27), the two dimensional temperature distribution in the canister wall was determined using the heat conduction code, HEATING-3⁽⁸⁾ and is shown in Figure 15 for the water cooled wall and in Figure 16 for the helium cooled wall (in both instances, the temperatures are relative to a fluid temperature of 0°). It should be pointed out that these results are all for the "plasma on" phase and are therefore based on an actual

wall loading of 1 MW/m^2 . Furthermore since the wall represents a very small thermal reservoir relative to the coolant flow thru it, the coolant flow must be shut off (or almost so) during the "plasma off" half of the cycle. Problems resulting from this on-off flow have not yet been examined in detail.

Having established the water flow and temperatures, all that remained was to establish the pressure required to suppress local boiling anywhere in the coolant path.

The remaining 55% of the heat to be recovered from the ceramic internals represents a much easier design problem since 1) the filler material has no structural function and 2) the operating temperatures in the He circuit were established based on HTGR technology and are well below the melting points of the carbides ($>2000^\circ\text{C}$).

The carbide bed could be formed in a variety of shapes and sizes. What was selected for this design was a rod bundle composed of rectangular rods with spaces to provide coolant passages between the rod clusters. To maximize the shielding function, the voidage permitted for these coolant passages was limited to 15%, all of which results in the process conditions indicated in Table 2.1. Since the thermal capacity of the ceramic rod bundle is large relative to the thermal capacity of the helium coolant stream, it is perfectly acceptable to

maintain the same coolant flow thru both the plasma on and plasma off phase of the cycle and to withdraw the heat at the average rate based on 0.5 MW/m^2 .

3.3 Header Flow Analysis

Headers or manifolds are important in a design such as this-important inside each canister to insure uniform cooling of the canister wall and equally important external to the blanket proper to insure uniform flow to each of the blanket modules.

There are two counteracting pressure effects of concern in these manifolds. On the one hand, flow friction causes the static pressure to decrease with distance thru the header. On the other hand, the continuous removal of fluid thru the manifold connections results in a decrease in velocity head in the feed header which causes the static pressure to increase with distance thru the header. In the return header the effect of flow friction and of velocity head operate in the same direction causing a more pronounced change in static head with distance thru the header. It is of course the difference in static head in the feed header and static head in the return header (at a location corresponding to the same coolant tube) which determines the flow thru the coolant path.

A detailed analysis based on the methods of Acrivos⁽⁹⁾ of

the internal canister headers lends to the conclusion that the maximum deviation in flow is only 3% for either the water or helium cooled shells which should not present any problem. For reference see Figures 28 and 29. A similar analysis for the external headers has yet to be made.

IV COMMERCIAL POWER REACTORS

4.1 Breeding

To translate the design described in some detail above to a commercial reactor, provision has been made for a higher first wall loading as well as for breeding tritium, which can be accomplished by adding to the high temperature ceramic core, neutron multipliers such as lead or beryllium as well as fertile material such as a lithium compound. Lazareth⁽¹⁰⁾ has shown that since aluminum is more transparent to neutrons than most other suggested first wall materials, breeding ratios will be relatively high and that Pb, PbO or Li_7Pb_2 can be substituted in whole or in part for the relatively less abundant Be with only a slight reduction in breeding ratio.

To accomodate the largersize plasma required in a commercial reactor, the individual canister size has been increased somewhat as was shown in Figure 3 and the number of canisters per module increased to 6 as shown in Figure 17, a cross section thru the module. An enlargement of the front end facing the plasma is shown in Figure 18. The region containing the neutron multipliers and the region showing the breeding compounds is clearly indicated. In the EPR design, the hot helium flowed thru the packed bed for the full length of the module, turned around and flowed back thru the full

length of the module. The commercial module being more than twice as long as the EPR module would have excessive pressure drop if this same flow pattern was used. Instead, the hot helium flows thru a header space which runs the full length of the module. The helium leaving the header space flows radially along the 70 cm depth of the bed to the outlet collection header. This much shorter path results in a reduced pressure loss and permits for larger mass flows. Figure 19 shows the arrangement of the upper horizontal modules in the 20° sector. As with the EPR, this tapered sector is covered with standard modules where possible and with modules composed of fore-shortened canisters at the right and left hand tapered edges. The exact number of standard modules and the details of the tapered end modules depends on the location of the divertor slot. In Figure 19, four standard modules are shown along with the right and left hand units.

A summary of typical blanket process conditions for a commercial reactor for both the water cooled first wall and for the helium cooled first wall are shown in Table 4.1. Of significance is the fact that the fraction of power to the cold circuit is reduced while the fraction to the hot circuit increases relative to the EPR design. The coolant temperatures are effectively the same as in the EPR case. The helium

Table 4.1

Typical Thermal and Hydraulic Characteristics of the
Aluminum Blanket in the Commercial Power Reactor

Reactor Power	5000 MW
Fraction of Power in Cold Circuit	0.34
Fraction of Power in Hot Circuit	0.66
First Wall Loading	2.5 MW/M ²

Cold Circuit Conditions

	<u>Option</u>	
	<u>5000 Series</u>	<u>SAP</u>
	<u>Al</u>	
Coolant	Water	He
Inlet Temperature, °C	180	200
Outlet Temperature, °C	195	380
Operating Pressure, psia	300	900
Flow Rate, g/sec	2.7x10 ⁷	1.81x10 ⁶
Channel Velocity, cm/sec	545	4200
Heat Transfer Coefficient, w/cm ² -°C	4.7	0.50
Blanket Pressure Drop, psia	31	20
Pumping Power as Fraction of Total Power	.0013	.008

Hot Circuit Conditions

Coolant	He
Inlet Temperature, °C	400
Outlet Temperature, °C	800
Operating Pressure, psia	300
Flow Rate, g/sec	1.58x10 ⁶
Velocity, cm/sec	1600
Blanket Pressure Drop, psia	9
Pump Power as Fraction of Total Power	0.014

Maximum Shelf Temperature

5000 Series Al	212 °C
SAP	398 °C

operating pressure for the SAP shell must be increased to 60 atm for reasonable blanket pressure drops.

Lithium aluminate as a fertile material for breeding tritium is entirely compatible with the overall design concepts presented above. The tritium diffuses out of this material quite readily and can be cold-trapped from the helium stream. Figure 20 shows scanning electron microscope photos of some 125-177 micron material after sintering at 1000°C for 12 weeks. Photo A which is 100X shows the individual particles to be roughly nodular. Photo B which is 5000X shows the structure to be plate like with an extremely large surface area and very many internal voids. Calculations made from photographs such as these indicate a surface area of as much as 30 m²/gm. Photographs such as those in Fig. 20 Photo B focus on a single granule or even just a small portion of it. To measure tritium release rates, few gram samples of LiAlO₂ were irradiated and the time required to achieve essentially complete tritium removal was measured. Samples were sintered for varying periods of time from 1 week to 12 weeks and the diffusion time measured with results shown in Figure 21. What is at first surprising is that the diffusion rate increases with sintering up to 4 weeks and then falls off somewhat, but even after 12 weeks is substantially higher

than for the unsintered material. There is a transition from a rhombohedral crystal lattice to a tetragonal crystal lattice which occurs at 900°C. This transition results in a volume increase of 30% and may account for the increased diffusion rates observed.

V ACTIVATION LEVEL

It would be extremely desirable in both the EPR and commercial reactors to have direct access to the outside of the primary shield to perform hands-on maintenance. Reactor components will have to be repaired or replaced, and coolant line connections and vacuum seals periodically broken in order to remove portions of the blanket. Such operations will be difficult, costly, and time consuming if done remotely. In a reactor with a sufficiently low level of induced radioactivity, these functions could be handled manually rather than remotely, thereby decreasing the complexity and cost of the reactor.

Aluminum is presently routinely available at 99.99% purity, the impurities being a few ppm each of Fe, Mn, Sn, Ti, Zn and Zr. Lazareth⁽¹¹⁾ has shown that based on commercially available aluminum, the major contributors to the activation of the blanket and shield materials are Al^{26} produced by $(n,2n)$ reactions on Al^{27} ; half-life of 7.3×10^5 years and Na^{24} produced by (n,α) on Al^{27} ; half-life of 15 hours. Shortly after shutdown, the Na^{24} decays to negligible levels. The residual contributors to the activation and the processes by which they were created are:

<u>Impurity</u>	<u>Reaction</u>	<u>Radioactive Product</u>	<u>Activation After 15 days (curies)</u>	<u>Energy of Associated Gamma-Rays (MeV)</u>
Mn ⁵⁵	(n, 2n)	Mn ⁵⁴	1900	.835
Zr ⁹⁰	(n, 2n)	Zr ⁸⁹	200	.909
	decay	Y ⁸⁹	200	.909
Zr ⁹⁶	(n, 2n)	Zr ⁹⁵	600	.756, .724
Zn ⁶⁶	(n, 2n)	Zn ⁶⁵	600	1.116

In the case of an EPR the gamma-ray dosage absorbed by a man standing outside the shield (15 days after reactor shutdown) was found to be $<10^{-8}$ REM/sec ($=9 \times 10^{-4}$ REM/day = .3 REM/yr).

It thus appears that residual activations of the blanket and shield are trivial in terms of dose during hands-on maintenance, and that in fact considerably higher impurity levels are allowable, if desired. Questions of dosage resulting from special regions (i.e., neutral beam ports) in the blanket/shield assembly have yet to be examined.

VI EFFECT OF PULSED MAGNETIC FIELDS ON MODULE STRUCTURE

The aluminum module shells will experience transient induced currents and force loadings whenever the magnetic field in the blanket changes. The only significant variation appears to be that of the poloidal field when the plasma switches on and off. Loss of the toroidal field will have to be a very rare event, since it will result in a long reactor down time. In addition unless a TF coil disrupts, the rate of decrease of toroidal field is too slow to cause any significant effect in the modular blanket.

The length of plasma burn cannot be specified with any exactitude, nor can the rate of rise and fall of the poloidal field during normal operation. In addition there exists the possibility of abnormally fast plasma shutoffs, e.g., via a disruptive instability. The effect of various rise and fall times of the poloidal field must thus be examined. This analysis considers the poloidal field from the plasma only.

Figure 30 shows the direction of currents and forces in the module shells when the pulsed poloidal field is along the axis of the module. Currents and forces in the backing plate and shields are not considered, for two reasons. First, these structures are much more rigid and less stressed than the shells,

and second, they will likely be made of bolted aluminum structural members which can easily be anodized to prevent current flow at junctures (the induced voltages are very small, on the order of millivolts). Consider the induced currents in a single one of the three logs on the module, with

A_s = area enclosed by mean perimeter of shell, cm^2

P_s = mean perimeter of shell, cm

Δs = thickness of shell, cm

B_p = poloidal field, gauss

B_T = toroidal field, gauss

Δt = time scale for B_p change, sec

ρ_s = resistivity of shell, Ωcm

The mutual inductance effects between logs is neglected, since it will cause a relatively small change in the induced forces.

The L/R time constant of the shell is substantially less than the shortest time scale considered, i.e., $\Delta t = 0.1$ sec, so the induced currents will be primarily controlled by the resistive impedance of the shell. Approximating $\dot{B}_p(t)$ by

$$\dot{B}_p(t) \simeq B_p / \Delta t$$

$$\dot{\Phi}_s = 10^{-8} (B_p / \Delta t) A_s$$

the induced current in the shell is then

$$I_s = \frac{\dot{\Phi}_s}{R_s} = 10^{-8} \frac{\Delta s B_p A_s}{\Delta t \rho_s P_s} \quad \text{amps/cm of shell}$$

and the force on the shell due to $I_s \times B_T$ is

$$F_s = \frac{I_s}{10} B_T \cos \theta \text{ dynes/cm}^2 \text{ of shell surface.}$$

This force is directed along the axis of the shell. Adjacent logs have oppositely directed forces, which will cancel if the shells have some degree of interlocking. The forces at the edges of the module can be transmitted to side supports. The only uncompensated forces are on the hemi-cylindrical unsupported shell facing the plasma.

Taking representative values [$A_s \sim 1500 \text{ cm}^2$, $P_s \sim 200 \text{ cm}$, $\rho_s \sim 8 \times 10^{-6} \Omega \text{ cm}$ (5000 series alloy at 200°C), $\Delta S \sim 2 \text{ cm}$, $B_p \sim 8 \times 10^3 \text{ G}$, $B_T \sim 50,000 \text{ G}$], we have (for $\theta = 0$)
 $I_s = 150 \text{ A/cm}$, $F_s = 0.75 \times 10^6 \text{ dynes/cm}^2$; $\Delta t = 1 \text{ sec}$
 $I_s = 1500 \text{ A/cm}$, $F_s = 7.5 \times 10^6 \text{ dynes/cm}^2$; $\Delta t = 0.1 \text{ sec}$

Even a very rapid turn off of the plasma ($\Delta t = 0.1 \text{ sec}$) does not cause an excessive pulsed force loading on the unsupported head of the shell. The maximum shear stress in the shell head generated by the force couple is quite moderate, i.e., approximately 1000 psi. Such a rapid turn off would presumably be a very unlikely event, and the shell would be exposed to this stress at most a few times during its lifetime. A more reasonable turnoff time of 1 second would cause a shear stress of only 100 psi, which should not significantly affect the shell.

Now consider the effect of a poloidal field transverse to the axis of the module, as in Figure 30. Such a poloidal field orientation can be found near the ends of the module [the angle of the poloidal field with respect to the module will change along its length. In the square type of blanket considered for easy blanket removal, the poloidal field from the plasma will have a 45° angle with respect to the normal from the module, at each end of the module, assuming a circular plasma].

The induced currents and forces due to the transverse component of poloidal field will than be in the ratio

$$\frac{I_s'}{I_s} = \frac{F_s'}{F_s} = \frac{A_s'}{A_s} \frac{P_s}{P_s'} \cos \alpha$$

where

I_s' = current induced by variation of transverse component of B_p , amp/cm

F_s' = force induced by variation of transverse component of B_p , dynes/cm² of surface

α = angle between plasma poloidal field and normal to module surface (45° at ends of module)

The ratio of area/perimeter for the transverse component of poloidal field is

$$\frac{A_s'}{P_s'} \approx W \quad \text{cm}$$

where $2W$ is the width of each log on the module. For the

same set of representative values, with $2W = 33$ cm,

$$\frac{I_s'}{I_s} = F_s'/F_s = \left(\frac{33}{2}\right) \left(\frac{200}{1500}\right) (0.707) = 1.5$$

Here the F_s force is in the direction of the normal to the module. The forces on the sides of the logs are oppositely directed for adjacent logs, so they can cancel each other if the logs are suitably interlocked. The forces on the unsupported hemicylindrical head cannot be cancelled, however, and will cause a couple pushing down on one half of the head and up on the other half. The equivalent average pressure loading of these forces on each shell head half is approximately 5 atm for $\Delta t = 0.1$ sec and 0.5 atm for $\Delta t = 1$ sec. [On the shell head, F_s decreases linearly from its maximum value at the log sidewall to zero at the center of the head.] The pressure loading from the helium coolant inside the shell is 20 atm, and it thus appears that the turn-off times as short as 0.1 second are probably tolerable.

If it is desired to reduce these pulsed forces, it should be possible to construct the shell with a thin inner continuous liner and make the bulk of the shell discontinuous at the backing plate. The shell could be bolted or clamped to the backing plate, so that adequate mechanical strength could be maintained for the shell. The voltage induced by the changing

poloidal field is very small, i.e., less than a volt, and a thin anodized layer on the outer shell would be quite adequate. The induced forces and currents could thus be reduced by a factor of 10 below the values shown above.

The problem of forces from pulsed fields appears to be more severe for liquid metal blankets, however, unless such blankets are subdivided into relatively small electrically isolated cells. The electrical resistances of current flow paths in liquid metal blankets are substantially less than in the aluminum modular blanket so that induced currents and forces will be substantially greater in liquid metal blankets. Solution for the current and forces is very difficult, however, since the liquid metal will be pumped by the induced currents, and the resultant MHD flow problem is very complex.

Consider the geometry of Figure 31 as representative of a liquid metal blanket. The Li containing module is assumed to have a radial thickness of $2\Delta r$, a width (in the direction of the toroidal field) of $2W$, and a height of $2Z$. A decreasing poloidal magnetic field will induce currents in the direction shown, which then act to pump the lithium in a closed loop as shown in Figure 31.

Two types of modules are possible. In the first, similar to that for UWMAC-1, there is considerable internal structure

and the flow of Li would be strongly hindered. In the limit, we can assume that for this first type of module the Li is essentially stagnant in terms of the VXB back electric field that flow produces. Body forces in the Z direction on the lithium due to the JXB interaction will be generated. These will be upwards on the right half of the module and downwards on the left half. If the poloidal field has a transverse component (i.e., in the r direction), the JXB body forces will be inwards on the left half of the module and outwards on the right half (for a poloidal field component directed towards the first wall). Assuming representative values ($\Delta r = 30$ cm, $\rho_{Li} = 50 \times 10^{-6}$ Ω cm, $B_p = 8$ kG, $B_T = 50$ kG) time scales of ~ 0.3 second for poloidal field changes will induce relatively large body forces on the Lithium (i.e., ~ 0.5 kgf/cm³) and the resultant pressure loadings and stresses on the module will be quite large. The transverse component of poloidal field is particularly worrisome since its time constant for field changes can be much greater than for the poloidal field component in the Z direction. If the time constant causing a given magnitude of induced currents due to poloidal field changes in the Z direction is ~ 0.3 second, the time constant for poloidal field changes in the r direction

will be $\left(\frac{W}{\Delta r}\right)^2$ times greater. In addition, the JXB body force on the Li will act directly outwards on half of the first wall, with pressures on the order of 10's of atm, which may rupture the first wall.

In the second type of module, similar to the ORNL EPR design, there is relatively little internal structure, with the Li being essentially stagnant in the module instead of pumped. Heat deposited in the module is transferred to internal helium coolant tubes. Under the action of the JXB body forces on the lithium, an internal circulation loop will be set up. For the case where the poloidal field is in the Z direction, the flow loop will have pumped sections in the middle of the module and loss sections at each end where the flow must reverse direction. Similar flow loops would be set up in the r direction if there is a transverse component of poloidal field. As in the first type of module, this is worrisome because of the longer time scale of induced currents and the outwards pressure on part of the first wall. In either case, however, relatively large fluid pressures can be expected, on the order of 10's of atmospheres.

VII POWER CONVERSION

A suitable power conversion cycle for either an EPR or commercial reactor using aluminum blanket modules employing both water and He as coolants is shown in Fig. 22. This flow sheet represents a combination of the process conditions* reported for the Summit Power Station of the Delmarva Power and Light Co.⁽¹²⁾ (which involves a helium cooled fission reactor) and the Comanche Peak Station of the Texas Utilities Generating Co.⁽¹³⁾ (which involves a PWR). The bulk of the helium which leaves the blanket at 727°C is used to raise steam at 510°C and 2400⁰ psia and to reheat the steam to 538°C. The steam conditions are identical to those of the Delmarva Plant. They are essentially the same as the steam conditions employed in many fossil fueled power plants. The high temperature steam cycle operates at a net thermal efficiency of about 36%.

Water from the first wall cooling circuit is flashed to produce saturated steam at 188°C and 173 psia. The liquid leaving the flash drum is recycled to the first wall. The saturated steam is superheated to 260°C using some of the high temperature He. This superheated steam drives a low pressure turbine in a cycle with a net thermal efficiency of only 22.2%.

*From Ref. 2 and not for the process conditions of the previous sections.

For the combined cycle, the overall efficiency is approximately 30%. This may be increased, for example, to 32% if the fraction of total energy to the water circuit is reduced.

An extensive study of this power conversion cycle was made⁽²⁾ in which the importance of decreasing the fraction of heat picked up in the aluminum wall circuit (because of its lower temp level) was demonstrated. Obviously a high priority is assigned to shifting the heat load toward the higher temperature circuit. Reduction of the shell structure wall as well as reducing the heat leak between the hot and cold regions are but two obvious means. The same design study⁽²⁾ showed the importance of increasing the temperature of the wall cooling circuit. The use of He cooling in SAP canisters points the way for that improvement.

It must be noted that the energy split between the hot and cold regions are markedly different for the EPR and commercial reactor (see Tables 2.1 and 4.1). The presence of the breeding and neutron multiplier materials in the hot region increases the heat deposition in this region.

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EPR-CIRCULAR PLASMA

Fig. 1

SCHEMATIC SHOWING MODULE REMOVAL
FIG 2

COMPARISON OF BLANKET MODULES FOR OUTER SIDEWALL OF FUSION REACTORS

Fig. 3

SIX AL. SHELLS ENCLOSING
NEUTRON MULTIPLIER, MODERATOR,
AND SOLID LITHIUM COMPOUND

MODULE WEIGHT = ~35 M TONS

DETAIL OF 20° SECTOR OF TOROUS
 SHOWING INNER & OUTER VERTICAL MODULES

FIG. 4

TYPICAL ARRANGEMENT OF
TOP & BOTTOM MODULES IN EPR

NOTE - WATER COOLANT CONNECTIONS
TO MODULES NOT SHOWN

BOTTOM ACCESS PORT FOR EPR

Fig. 6

BOTTOM ACCESS PORT FOR EPR

Fig. 7

TOP ACCESS PORT FOR EPR

Fig. 8

PLAN VIEW SHOWING POSITIONING TRACKS IN FIXED SHIELD
FOR BOTTOM MODULE INSERTION AND REMOVAL

Fig. 10

PLAN VIEW SHOWING POSITIONING TRACKS IN FIXED SHIELD
FOR TOP MODULE INSERTION AND REMOVAL

Fig. 11

TYPICAL SHELL COOLING CONFIGURATION
He OR H₂O COOLING (OPTION SHOWN)

FIG 12 MODULE SHOWING THREE
INDIVIDUAL CANISTERS

TOTAL NEUTRON FLUX vs DISTANCE

Fig. 13

TOTAL VOLUMETRIC HEAT DEPOSITION RATES

Fig. 14

TEMPERATURES SHOWN ARE IN °C
ABOVE COOLANT TEMPERATURE

TEMPERATURE DISTRIBUTION IN WROUGHT ALUMINUM FIRST WALL

Fig. 15

TEMPERATURES SHOWN ARE IN °C
ABOVE COOLANT TEMPERATURE

TEMPERATURE DISTRIBUTION IN SAP FIRST WALL

Fig. 16

CROSS SECTION OF ALUMINUM MODULE FOR
COMMERCIAL FUSION REACTOR
[UWMAK SIZE PLASMA]
54 SIDEWALL MODULES

Fig. 17

DETAIL OF ALUMINUM CELL FOR
COMMERCIAL POWER REACTOR

Fig. 18

TYPICAL ARRANGEMENT OF TOP & BOTTOM MODULES IN
UWMAX TYPE REACTOR

Fig. 20 - Scanning Electron Microscope Pictures of LiAlO_2 Particles After Sintering at 1000°C for 12 Weeks (Particle Size 125-177 Microns).

FIGURE 23- Cross Section of UWMAK-I Reactor Building

	<u>Stresses in psi</u>		
	<u>Inside</u>	<u>Outside</u>	<u>Average</u>
AA	1370	1960	1640
BB	1840	1550	1650
CC	3080	1030	1700
DD	3510	1150	2180

Max Stress in FP = -10,580psi

Figure 24

Stresses in Edge Canister With Adjacent
Module Support

Figure 25
Stresses in Edge Canister Without Adjacent Support

TWO DIMENSIONAL MODEL USED TO COMPUTE TEMPERATURE
 DISTRIBUTION IN FIRST WALL OF WROUGHT
 ALUMINUM BLANKET

Fig. 26

TWO DIMENSIONAL MODEL USED TO COMPUTE TEMPERATURE
 DISTRIBUTION IN FIRST WALL OF SAP BLANKET

Fig. 27

Fig. 28

PRESSURE DISTRIBUTION IN WATER MANIFOLD, SHELL COOLING

Fig. 29

PRESSURE DISTRIBUTION IN HELIUM MANIFOLD, SHELL COOLING

F_s ALONG AXIS OF MODULE SHELLS

I_s ALONG AXIS OF MODULE SHELLS

PULSED CURRENTS & FORCES IN
ALUMINUM MODULAR BLANKETS

Fig. 30

Representation of Liquid Metal Blanket
Fig. 31